



Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier

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ABSTRACT

A process of conversion of solid carbonaceous fuel into combustible gas by partial combustion is known as gasification. The resulting gas, known as producer gas, is more versatile in its use than the original solid biomass. In the present study, a downdraft biomass gasifier is used to carry out the gasification experiments with the waste generated while making furniture in the carpentry section of the institute's workshop. *Dalbergia sisoo*, generally known as sesame wood or rose wood is mainly used in the furniture and wastage of the same is used as a biomass material in the present gasification studies. The effects of air flow rate and moisture content on biomass consumption rate and quality of the producer gas generated are studied by performing experiments. The performance of the biomass gasifier system is evaluated in terms of equivalence ratio, producer gas composition, calorific value of the producer gas, gas production rate, zone temperatures and cold gas efficiency. Material balance is carried out to examine the reliability of the results generated. The experimental results are compared with those reported in the literature.

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1. Introduction

Biomass is the term used to describe all biologically produced matter and it is the name given to all earth's living matter (Babu, 2008). Biomass energy is derived from the plant sources, such as wood from natural forests, waste from agricultural and forestry processes and industrial, human or animal wastes. It is a natural process that all biomass ultimately decomposes to its molecules with the release of heat. And the combustion of biomass imitates the natural process. So the energy obtained from biomass is a form of renewable energy and it does not add carbon dioxide to the environment in contrast to the fossil fuels (Twidell, 1998). Of all the renewable energy sources, biomass is unique in that it effectively stores solar energy inherently. Furthermore, it is the only renewable energy source of carbon and is able to convert into convenient solid, liquid and gaseous fuels (Demirbas, 2001). Wood is still a predominant fuel in many non-OPEC (Organization of the Petroleum Exporting Countries), tropical, developing countries and it will continue to be used for many years. Wood as a fuel is being used in the domestic (for cooking and water heating), commercial (water heating) and industrial (for water heating and process heat) sectors and also in rural industries, like brick kilns,

potteries etc. It competes well with fossil fuels, because it is renewable, and with soft energies like solar and wind, on account of its energy storage capability (Demirbas, 2000). In nature, biomass is not concentrated, and so, the use of naturally occurring biomass requires transportation, which increases the cost and reduces the net energy production. Apart from transportation, incomplete combustion of biomass generates a concern among the environmentalist, as it may produce organic particulate matter, carbon monoxide and other organic gases. If high temperature combustion is used, oxides of nitrogen would be produced. The health impact of air pollution is a significant problem in developing countries, where fuel wood is burnt inefficiently in open fires for domestic cooking and space heating (Demirbas, 2001).

The conversion technologies for utilizing biomass can be separated into four basic categories: direct combustion processes, thermochemical processes, biochemical processes and agro-chemical processes (Babu, 2008). There has been an increasing interest for thermochemical conversion of biomass and urban wastes for upgrading the energy in terms of more easily handled fuels, namely gases, liquids, and charcoal in the past decade. The thermochemical conversion of biomass (pyrolysis, gasification, combustion) is one of the promising routes among the renewable energy options of future energy. It is a unique renewable form of energy with many ecological advantages. In the thermochemical conversion technologies, biomass gasification has attracted the highest interest as it offers higher efficiencies compared to combustion and pyrolysis. Gasification is a process of conversion of solid carbonaceous fuel into combustible gas by partial combustion (Basu,

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2006). The resulting gas, known as producer gas, is a mixture of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. The producer gas is more versatile in its use than the original solid biomass. It is burnt to produce process heat and steam or used in gas turbines to produce electricity (Babu and Sheth, 2006; Sheth and Babu, 2009).

Sheng (1989) introduced the properties of biomass gasifier and the gasifying reaction processes. Various fuels usually considered unusable or low-value wastes, such as sawdust, wood chips, corn cobs, nut shells, rice hulls, etc., are used in the biomass gasifier to produce a high calorific value gas. It is concluded that the gas produced by downdraft gasifiers is tar-free and could be used directly to drive most of the internal combustion engines. Maschio et al. (1994) studied the influence of the operating conditions on gasification of biomass at a pilot plant scale. The entire process of pyrolysis and gasification is carried out using two reactors in series. Rice husk was successfully used as a biomass material in a downdraft biomass gasifier by Chowdhury et al. (1994). Jorapur and Rajvanshi (1995) developed a gasifier running on chopped sugarcane leaves (1–10 cm). The experimental system consists of a throatless cylindrical gasifier, a gas conditioning system and a diesel-powered generator along with its control panel. Experiments are carried out by varying air velocity in the range of 0.032–0.099 m/s, and gasification rate in the range of 1.8×10^{-2} – 4.3×10^{-2} kg/m²s. Jorapur and Rajvanshi (1997) in their subsequent study reported the development of a commercial-scale (1080 MJ h⁻¹) gasification system using low-density biomass such as sugarcane leaves, bajra stalks, sweet sorghum stalks and bagasse for thermal applications. Di Blasi et al. (1999) designed a laboratory scale countercurrent fixed bed gasification plant and constructed to produce data for process modeling and to compare the gasification characteristics of several biomass materials such as beechwood, nutshells, olive husks, and grape residues. Zainal et al. (2002) performed experimental study on a downdraft biomass gasifier using wood chips and charcoal. The effect of equivalence ratio (experimental to stoichiometric ratio of air flowrate per unit biomass consumption) on the gas composition, calorific value and the gas production rate is reported. Dogru et al. (2002) carried out gasification studies using hazelnutshell as a biomass. Hazelnutshell is an agricultural waste and abundantly available in Turkey. Jayah et al. (2003) used a downdraft biomass gasifier using rubber wood as biomass in tea drying unit. Factors affecting the conversion efficiency are identified by performing experiments under various operating conditions. In order to assess the potential of the saw dust as a biomass material, a fixed bed, downdraft, stratified and open top gasifier is used by Wander et al. (2004). Hanaoka et al. (2005) studied the effect of woody biomass components on air-steam gasification using a downdraft fixed bed gasifier operated at 1173 K and at atmospheric pressure. Sharma (2007) used an open top downdraft biomass gasifier of capacity 20 kWe. Steady state temperatures at different locations inside the reactor are measured using K-type thermocouples at various values of pressure and air flow rate.

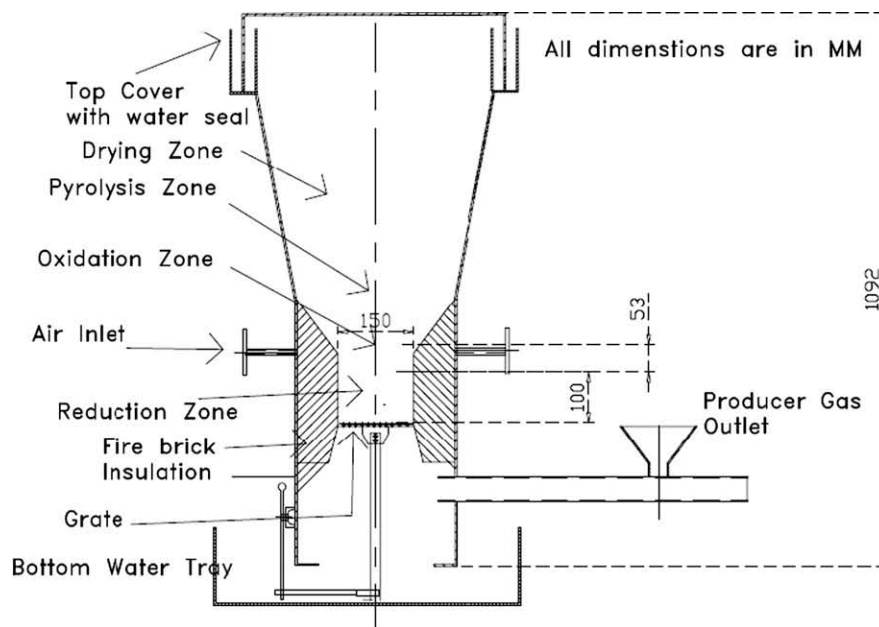
In the present study, gasification experiments are carried out with the wood waste as a biomass material in a downdraft biomass gasifier. The biomass used in the present study is the waste generated in furniture making, collected from the carpentry section of the institute's workshop. Mainly two wood species are used to make furniture in the workshop namely *Dalbergia sisoo*, generally known as sesame wood or rose wood and teak wood. Teak wood is costlier in comparison to sesame wood and also not easily available. Generally the furniture waste is used either for direct combustion or sold to pottery makers at a very cheap rate. Pottery making is an energy intensive process due to high temperature requirement in the firing kiln. In rural part of India, many small-scale pottery making industries use agricultural waste or wood

waste as a fuel. The disadvantages associated with this process are poor control of temperature in the firing kiln and the large amount of ash and other particulates in the emission (Noyes, 1993). These can be certainly avoided by applying biomass gasification technology. The producer gas generated from the biomass gasifier using wood wastes can be directly fired in the kiln with a better control over operating conditions. Apart from these, as the producer gas is almost tar-free due to downdraft design of gasifier, it can be used in an engine to generate electricity locally after preliminary gas cleaning. The uniqueness of this work is distinguished from earlier studies by covering wide range of equivalence ratio (0.167–0.355) in comparison to other researchers. The optimum value of equivalence ratio, which produces gas with maximum calorific value, is found. The results of the present study are useful to choose the operating conditions of the downdraft biomass gasifier. Waste generated while furniture preparation of sesame wood is collected and cut into appropriate sizes to feed the downdraft biomass gasifier. The effects of air flow rate and moisture content on biomass consumption rate and the quality of the producer gas are studied by performing experiments. The performance evaluation of the biomass gasifier system is carried out in terms of the equivalence ratio, producer gas composition, calorific value of the producer gas, gas production rate, zone temperatures and cold gas efficiency.

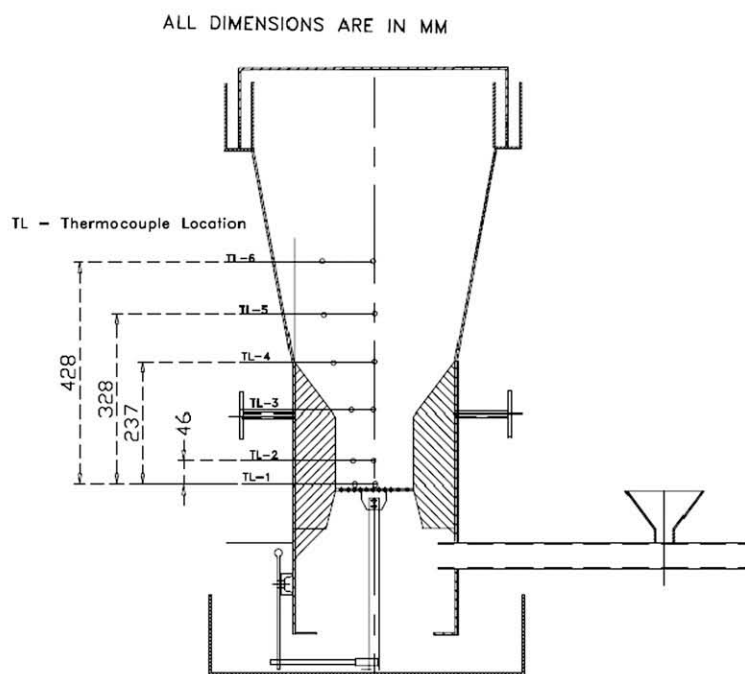
2. Experimental setup and procedure

2.1. Experimental setup

The downdraft gasifier has four distinct reaction zones: (1) drying, (2) pyrolysis, (3) oxidation and (4) reduction. An Imbert downdraft biomass gasifier is shown in Fig. 1a. An Imbert downdraft biomass gasifier is the one, which has throated combustion zone and different diameter for pyrolysis and reduction zone unlike stratified downdraft biomass gasifier in which gasifier diameter is uniform through out the gasifier (Reed and Das, 1988). In downdraft gasifiers, pyrolysed gas and moisture generated in pyrolysis and drying zone, respectively flow downwards. The pyrolysis gases pass through a combustion zone followed by a hot bed of char which is supported by a grate. Biomass is fed to the gasifier and oxidized in the zone where continuous air is supplied from two air nozzles. The heat generated in the combustion zone is transferred to the pyrolysis and drying zone. Released heat from the biomass combustion raises the temperature of the biomass particles resting above the oxidation zone and thus they get pyrolysed. The biomass particles are decomposed into volatiles and charcoal in the pyrolysis zone. The basic phenomena that takes place during pyrolysis are: (1) heat transfer from a heat source leading to an increase in temperature inside the fuel, (2) initiation of pyrolysis reactions due to this increased temperature leading to the release of volatiles and the formation of char, (3) outflow of volatiles resulting in heat transfer between hot volatiles and cooler unpyrolysed fuel, (4) condensation of some of the volatiles in the cooler parts of the fuel to produce tar, and (5) auto-catalytic secondary pyrolysis reactions due to these interactions (Babu and Chaurasia, 2004a, b, c, d). Released volatiles from each of the biomass particles flow downward in the packed pyrolysis bed. The rate of volatiles release depends on particle size and temperature within the single particle. Due to high temperature of the combustion zone, tar of the pyrolysed gas mixture cracks into non-condensable gases and water. The cracked pyrolysed gas mixes with the carbon dioxide generated due to combustion and the inert N₂ present in the air. This gaseous mixture passes over the hot bed of charcoal and undergoes endothermic reduction reactions. Water seal is provided at the top of the gasifier to maintain the downward flow. The total



(a) Various parts, zones and dimensions of the unit



(b) Location of Thermocouples

Fig. 1. Schematic diagram of an Imbert downdraft biomass gasifier.

height of the gasifier is 1.1 m and the diameter at the pyrolysis zone is 310 mm and the diameter at the reduction zone is 150 mm. The height of the reduction zone is 100 mm and that of oxidation zone is approximately 53 mm. The height of the pyrolysis zone depends upon the biomass loading. The charcoal in the reduction zone is supported by a movable grate at the bottom of the gasifier. The ash produced during gasification is removed by rotating the grate using the lever arrangement provided to unclog the grate. By moving the grate, grate clogging and bridging of the biomass can be avoided thereby causing greater amount of biomass to undergo gasification.

To measure the temperature of various zones in the gasifier, thermocouples are placed inside the gasifier at different locations. There are six pairs of chromel–alumel thermocouples, each pair placed at different heights of the gasifier (Fig. 1b) so as to cover all the zones. In each pair, one thermocouple is placed at the center of the gasifier ($r = 0$) while the other is placed at a half radius distance ($r = R/2$). Two pairs of thermocouples are placed in the reduction zone of the gasifier, one at the end of the reduction zone that is close to the grate and one at a height of 46 mm from the grate. One pair of thermocouples is placed in the oxidation zone present at the level of the air inlet nozzles. Three pairs of the thermocouples are

placed in the pyrolysis zone at height of 237, 328, and 428 mm from the grate, respectively in the biomass gasifier.

2.2. Experimental procedure

Water is filled in the container placed below the gasifier and also in the circular trough at the top of the gasifier which act as seals and hence to prevent the gas from escaping out of the gasifier. About 500 g of charcoal (collected from the residue of the wood based furnace, used for mass cooking locally) is dumped as a heap into the reduction zone of the gasifier above the grate. The initial charcoal used in the present experimentation is of the same quality as that generated in the gasification experiments by pyrolysis of wood. The air is introduced in the biomass gasifier through nozzles and its flow rate, which is maintained constant through a gate valve, is measured using a rotameter. Biomass is dumped in to the oxidation zone of the biomass gasifier and around 25 ml of diesel is poured to aid the combustion of biomass. Once combustion starts properly and spread across the oxidation zone which generally takes about 3–4 min, additional 3 kg of biomass is dumped inside the gasifier and it is closed from the top by cover. It is observed that by the time combustion starts properly in the oxidation zone most of the diesel gets combusted due to volatility of diesel and very high temperature generated in the oxidation zone. The time at which the cover is closed, is taken to be the starting time of the experiment. Temperatures are recorded at each location after every five minutes. The samples of producer gas coming out from the gas burner are collected in the syringes at five minutes interval. Results presented in this study are the averaged values obtained over 5 min interval each for five intervals. The averaging should take care of the variation with respect to time. Sampled gas is analysed with gas chromatograph (NUCON 5765) with thermal conductivity detector. Each experimental run is carried out for 25 min. At the end of the experiment any leftover biomass and charcoal is removed from the gasifier. In the present experimental study, air flow rate is varied from 1.8 to 3.4 m³/h and moisture content is varied from 4% to 12%. It is found that the locally available biomass contains moisture content ranging from 4% to 13% only and hence the experiments are conducted with this range only. Biomass consumption rate is found to vary from 1.0 to 3.6 kg/h.

3. Results and discussion

3.1. Biomass characteristics

The furniture waste of *D. sisoo*, generally known as sesame wood or rose wood is used as a biomass in the present gasification studies. Table 1 lists the physical properties, the proximate analyses, ultimate analyses and chemical analyses of the *D. sisoo*. Higher

heating value (HHV) is calculated using the empirical formula given by Eq. (1) reported in the literature (Parikh et al., 2005).

$$\text{HHV (MJ/kg)} = 0.3536 \text{ FC} + 0.1559 \text{ VM} - 0.0078 \text{ ASH} \quad (1)$$

3.2. Biomass gasification

The details on the range of parameters varied in this experimental study are shown in Table 2. Biomass consumption rate is found to vary from 1.0 to 3.6 kg/h for an air flow rate varying from 1.85 to 3.4 m³/h, respectively. Moisture content is varied from 0.0437 to 0.1145 wt fraction on wet basis. In order to reduce the number of parameters on which the performance of the biomass gasifier depends, an equivalence ratio is defined to reflect the combined effect of air flow rate, rate of wood supply and duration of the run. The equivalence ratio (Φ) for each run is calculated by Eq. (2) (Reed and Das, 1988).

$$\Phi = \left(\frac{\text{Air Flow Rate}}{\text{Biomass Consumption Rate}} \right) / \left(\frac{\text{Air Flow Rate}}{\text{Biomass Consumption Rate}} \right)_{\text{Stoichiometric}} \quad (2)$$

The stoichiometric ratio of air flow rate to biomass consumption rate is 5.22 m³ air/kg of wood (Zainal et al., 2002). The values of equivalence ratio are calculated for each run and reported in Table 2. Material balance is carried out to examine the reliability of the results generated. Total mass input includes feed stock, air and total water input and total mass outputs comprise of charcoal produced and producer gas outputs. The ash generated in the experiments and some small pieces of charcoal passed through grate and falls into the bottom water tray. Those wet ash and small charcoal pieces are not collected and hence not considered in the analysis. The usual method to quantify the discrepancies in the mass balance is the closure of the mass balance which is defined as the percentage ratio of the total output mass to that of the total input mass (Dogru et al., 2002). Table 3 shows the detailed mass input, mass output and the mass closure for all the experimental runs. The average mass balance closure was found to be 89% over six experimental runs.

3.2.1. Effect of moisture content

The effect of moisture content on biomass consumption rate is shown in Fig. 2. It is found that with an increase in the moisture content, the biomass consumption rate decreases. For higher moisture content of biomass, the energy requirement for drying increases and reduces the biomass pyrolysis. The biomass moisture content greatly effects both the operation of the gasifier and the quality of the product gas. The constraint of moisture content for gasifier fuels are dependent on type of gasifier used. Higher values of moisture content could be used in updraft systems but the upper

Table 1
Characteristics of *Dalbergia sisoo*.

Physical properties			
Size (mm ³)	Absolute density (kg/m ³)	Bulk density (kg/m ³)	
25.4 × 25.4 × 25.4	1170	605	
Proximate analysis (% by wt. dry basis)*			
Fixed carbon (FC)	Volatile matter (VM)	ASH	Calculated HHV (MJ/kg)
15.70	80.40	3.90	18.06
Ultimate analysis (% by wt. dry basis)*			
Carbon	Hydrogen	Oxygen	Nitrogen
48.6	6.2	44.87	0.33
Chemical analysis (% by wt.)*			
Cellulose	Hemi cellulose	Lignin	Extractives
36.75	11.30	43.65	8.30

* Source: Bhawe (2001).

Table 2

Biomass gasification experimental run details.

Run	Air flow rate (m ³ /h)	Initial moisture content (wt fraction, wet basis)	Biomass consumption rate (kg/h)	Equivalence ratio (Φ)
1	2.7765	0.1145	2.10	0.2533
2	3.3935	0.0437	3.63	0.1791
3	1.8510	0.0437	2.12	0.1673
4	2.7765	0.0437	2.67	0.1992
5	2.7765	0.073	2.59	0.2054
6	1.8510	0.10	1.00	0.3546

Table 3

Material balance.

Run	Equivalence ratio (Φ)	Air flow rate (Nm ³ /h)	Total input (kg/h)		Total output (kg/h)			Mass balance closure (%)
			Air flow rate (kg/h)	Biomass consumption rate (kg/h)	Producer gas flow rate (Nm ³ /h)	Producer gas flow rate (kg/h)	Char produced (kg/h)	
1	0.2533	2.7765	4.91441	2.10	3.83296	6.1634	0.312	92.316
2	0.1791	3.3935	6.0065	3.63	4.75711	7.64944	0.288	82.369
3	0.1673	1.8510	3.27627	2.12	2.37097	3.81251	0.3	76.21
4	0.1992	2.7765	4.91441	2.67	4.05672	6.5232	0.24	89.172
5	0.2054	2.7765	4.91441	2.59	4.19383	6.74368	0.24	93.061
6	0.3546	1.8510	3.27627	1.00	2.51031	4.03658	0.324	99.727

limit acceptable for a downdraft reactor is generally considered to be around 40% on dry basis (Dogru et al., 2002).

3.2.2. Effect of air flow rate

The effect of air flow rate on biomass consumption rate is shown in Fig. 2. It is found that with an increase in the air flow rate, biomass consumption rate increases. The increase in the air flow rate provides more oxygen to oxidize and higher amount of biomass would get combusted. The energy released will increase the rate of drying and pyrolysis. Biomass consumption rate increases not only due to a higher combustion rate, but also due to the enhanced pyrolysis and drying rate.

3.3. Performance evaluation of biomass gasifier

The performance of the biomass gasifier system is evaluated in terms of the producer gas composition, the calorific value of producer gas, gas generation rate, zone temperatures and cold gas efficiency.

3.3.1. Producer gas composition

The gas composition of producer gas sampled at five minutes interval during gasification experiments is found using gas chro-

matograph (NUCON 5765) with thermal conductivity detector. The averaged gas composition for each experimental run is plotted against the equivalence ratio of the same experimental run and shown in Fig. 3. Molar fraction of nitrogen and carbon dioxide decreases with an increase in Φ upto a value of $\Phi = 0.205$ and for higher values of Φ , molar fraction of nitrogen and carbon dioxide increases. The fraction of carbon monoxide and hydrogen shows an increasing and decreasing trend just opposite to that of nitrogen and carbon dioxide. A higher value of Φ represents a higher air flow rate for a specific biomass consumption rate which leads to more amount of CO₂ production in combustion zone and more amount of N₂ entry along with air flow. The conversion of CO₂ to CO depends upon the rate of reactions occurring in the reduction zone and length of the reduction zone. With an increase in Φ from 0.16 to 0.205, increased CO₂ amount in combustion zone is converted into carbon monoxide and hydrogen, and thereby the fraction of CO and H₂ increases with Φ till a value of $\Phi = 0.205$ and fraction of CO₂ and N₂ decreases. The increase in CO₂ and decrease in CO & H₂ fractions for the equivalence ratio higher than 0.205 represents that CO₂ produced in combustion zone is in excess to that of the conversion capacity of reduction bed. The increase in

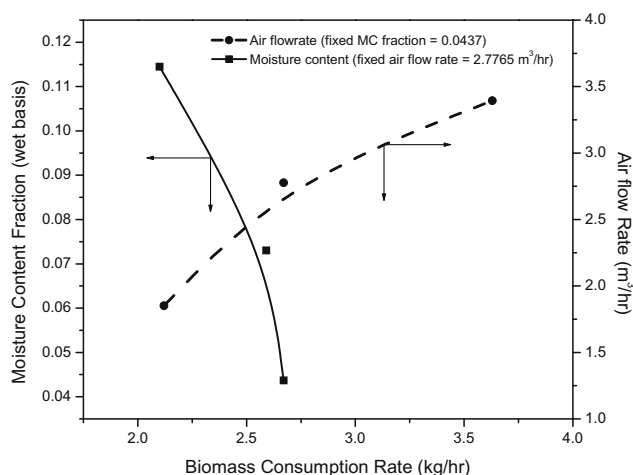


Fig. 2. Effect of moisture content (for an air flow rate of 2.7765 m³/h) and of air flow rate (for a MC of 0.0437) on biomass consumption rate.

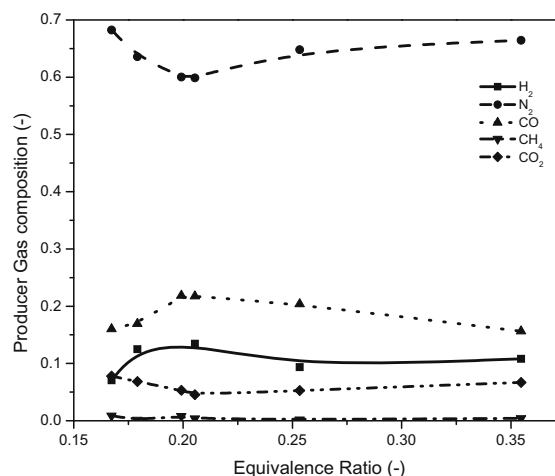


Fig. 3. Effect of equivalence ratio on producer gas composition.

N_2 fraction for the Φ value variation from 0.205 to 0.36 is due to a more amount of N_2 entry along with the air flow.

3.3.2. Zone temperatures

Fig. 4 shows the variation of the average temperature of pyrolysis and oxidation zone of the downdraft biomass gasifier with the equivalence ratio. The temperature of oxidation zone varies from 900 °C to 1050 °C and that of pyrolysis zone between 260 °C and 550 °C. It clearly indicates that both temperature profiles pass through a maximum at an equivalence ratio of 0.205. The oxidation zone temperature depends upon the heat released due to the biomass combustion and air flow rate. As air flow rate increases, it provides more oxygen to oxidize but also brings inert N_2 , which acts as a heat carrier and reduces the temperature of the oxidation and pyrolysis zone. The maximum value of temperatures in the pyrolysis and oxidation zones represents the optimum amount of equivalence ratio. Fig. 3 also supports that at an optimum equivalence ratio ($\Phi_{opt} = 0.205$) the fractions of carbon monoxide and hydrogen are the maximum and the fraction of carbon dioxide is the minimum.

3.3.3. Calorific value of gas

The variation of calorific value of the producer gas with equivalence ratio is presented in Fig. 5. Calorific value is calculated using

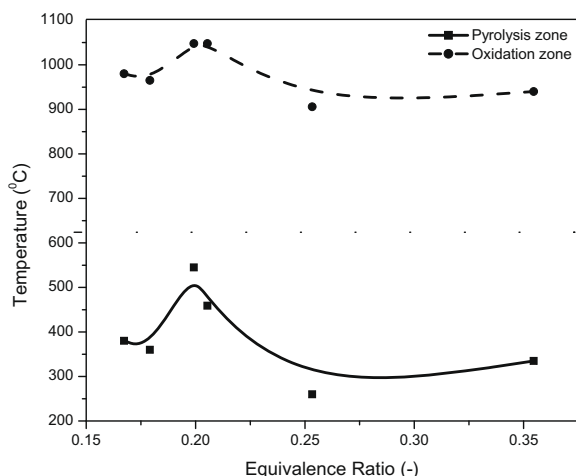


Fig. 4. Effect of equivalence ratio on zone temperatures.

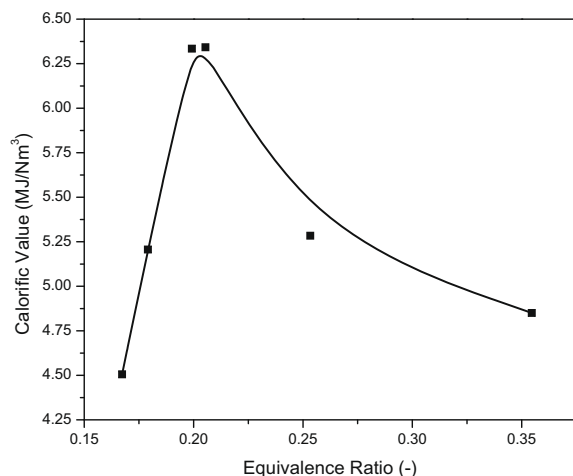


Fig. 5. Effect of equivalence ratio on calorific value of producer gas.

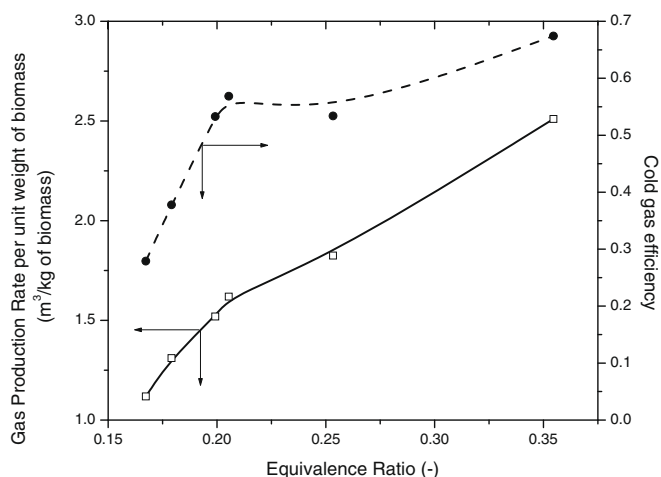


Fig. 6. Effect of equivalence ratio on producer gas production rate per unit weight of biomass and on cold gas efficiency.

the composition of the producer gas. Carbon monoxide and hydrogen are the main components of the producer gas and are responsible for higher calorific value. It is found that at an equivalence ratio of 0.17 the calorific value is the least at 4.5 MJ/Nm³. With a small increase in the equivalence ratio at $\Phi = 0.205$, the calorific value reaches to a maximum of 6.34 MJ/Nm³ and then follows the decreasing trend. For the equivalence ratio higher than 0.205, calorific value steadily decreases with a further increase in the equivalence ratio. The increasing and decreasing trend of calorific value variation is exactly same as that of carbon monoxide and hydrogen variation with equivalence ratio as shown in Fig. 3.

3.3.4. Gas production rate

Fig. 6 shows the effect of equivalence ratio on the producer gas production rate per unit weight of biomass (Nm³/kg). It clearly shows that with an increase in the equivalence ratio, producer gas production rate continuously increases. Higher equivalence ratio signifies higher air flow rate for a specific biomass consumption rate. Hence although after a certain value of the equivalence ratio, calorific value of the producer gas deteriorates due to higher amounts of carbon dioxide as depicted in Figs. 3 and 5, the production rate of producer gas continue to increase.

3.3.5. Cold gas efficiency

Cold gas efficiency is defined as the ratio of energy of the producer gas per kg of biomass to the HHV of the biomass material (Eq. (3)).

Cold gas efficiency

$$= \frac{(\text{Calorific value})(\text{Gas Production per weight of biomass})}{\text{Higher Heating Value of the biomass}} \quad (3)$$

The variation of cold gas efficiency with equivalence ratio is given in Fig. 6. As given in Eq. (3) cold gas efficiency depends upon the calorific value and the amount of producer gas released at constant HHV of biomass. The amount of producer gas increases continuously and the calorific value passes through a maximum with an increase in the equivalence ratio. Cold gas efficiency is at a lowest value of 0.25 for an equivalence ratio value of 0.17. The value of cold gas efficiency becomes almost double with a small increase in the equivalence ratio at $\Phi = 0.205$. The effect Φ of on cold gas efficiency is comparatively lower for higher values of equivalence ratio. Cold gas efficiency increases from 0.5 to 0.6 for a change in the equivalence ratio from 0.2 to 0.35.

Table 4

Comparison of the experimental results with published in literature.

Research group	Biomass species used	Optimum equivalence ratio	Calorific value (MJ/Nm ³)	Gas production rate per unit weight of biomass (Nm ³ /kg)	Cold gas efficiency (%)
Dogru et al. (2002)	Hazelnutshell	0.276	5.15	2.73	80.91
Zainal et al. (2002)	Furniture wood + charcoal	0.388	5.62	1.08	33.72
Present study	Furniture waste of <i>Dalbergia sisoo</i>	0.205	6.34	1.62	56.87

3.4. Comparison of performance of biomass gasifier

The experimental results are compared with those reported in the literature. Hazelnutshell as a biomass is used in the gasification studies carried out by Dogru et al. (2002). The range of air-to-fuel ratio varied is 1.37–1.64 Nm³/kg and that of equivalence ratio varied is 0.262–0.314. The optimum operation of the gasifier is found to be between 1.44 and 1.47 Nm³/kg of air-to-fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate, which produces the producer gas with a calorific value of about 5 MJ/m³. Zainal et al. (2002) performed experimental study on a downdraft biomass gasifier using wood chips and charcoal. Zainal et al. (2002) varied the equivalence ratio from 0.259 to 0.46. It is found that the calorific value increases with equivalence ratio and reaches a peak value of 0.388, for which the calorific value is reported to be 5.34 MJ/Nm³. Table 4 shows the comparison of experimental results corresponding to the optimum equivalence ratio or air-to-fuel ratio for the present work with reported by Dogru et al. (2002) and Zainal et al. (2002). It shows that highest calorific value of gas is produced in the present study.

4. Conclusions

Based on the results of this study, the conclusions drawn are:

- With an increase in the moisture content, biomass consumption rate decreases and with an increase in the air flow rate biomass consumption rate increases.
- Molar fraction of N₂ and CO₂ decrease with an increase in equivalence ratio (Φ) till $\Phi = 0.205$, and for higher values of Φ , they increase. The fraction of CO and H₂ shows increasing and decreasing trend exactly opposite to that of N₂ and CO₂.
- The calorific value, pyrolysis zone temperature and the oxidation zone temperature are maximum at $\Phi = 0.205$. However, the calorific value decreases for an equivalence ratio ranging from 0.205 to 0.35.
- With an increase in Φ , the production rate of producer gas continuously increases.
- The value of cold gas efficiency is 0.25 for $\Phi = 0.17$. It becomes almost double with a small increase of 0.035 in the value of Φ . The effect of Φ on cold gas efficiency is comparatively lower for higher values of Φ .
- The optimum equivalence ratio is 0.205 for the downdraft biomass gasifier studied.

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